論文の内容の要旨

A Study of Neutrons Associated with Neutrino and Antineutrino Interactions on the Water Target at the T2K Far Detector

(T2K 後置検出器における水標的でのニュートリノ及び反ニュートリノ反応に伴う中性子の研究)

氏名　阿久津　良介

Introduction

Neutrinos are accommodated by the Standard Model of particle physics. Although there have been remarkable efforts, their nature has not been fully understood yet since they interact extremely weakly with other particles. Understanding of one of the unknown nature, charge-parity violating phase in the lepton sector, would provide information that may explain the imbalance of matter and antimatter in the universe. Since neutrinos are the second most dominant particles, they may deliver unique information about the evolution of the universe. To address such information, further improvements to analysis methods are needed.

In future experiments employing water Cherenkov detectors, it can be quite valuable to utilize neutrons associated with neutrino interactions in water. Utilization of such neutrons are expected to improve their physics analysis methods. These neutrons are produced via the three processes: primary ν-nucleon interaction in the target nucleus, hadronic final-state interaction inside the nucleus, and hadronic secondary interaction in detector medium. Figure 1 shows a schematic drawing of the neutron production by these processes. Although a precise prediction of the neutron production by a Monte Carlo (MC) simulation is essential for these analyses, current MC simulations, however, produce different predictions due to all the three processes. In addition, no extensive study has been made for water. Therefore, it is quite worth studying those neutrons and evaluating the validity of the simulations by using well understood neutrino source. This thesis presents the first measurement of those neutrons for accelerator neutrinos and antineutrinos at the T2K far detector.

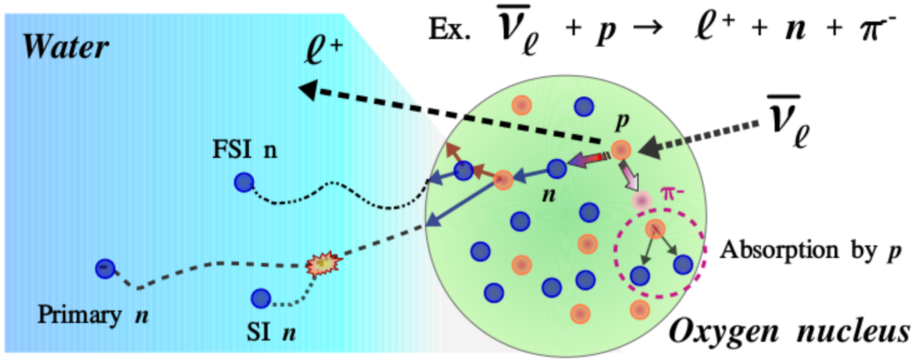

Figure 1: A schematic drawing of neutron productions by primary $\bar{\nu}$-nucleon interaction inside oxygen nucleus, hadronic-final-state interactions inside the nucleus, and hadronic secondary interactions in water. In this case, the primary reaction $\bar{\nu}_\ell + p \to \ell^+ + n + \pi^-$ is used.

The T2K experiment

The Tokai-to-Kamioka (T2K) experiment is a long-baseline ν oscillation experiment in Japan. It uses a primarily ν_μ ($\bar{\nu}_\mu$) beam produced at J-PARC, with a peak energy of 0.6 GeV. The beam neutrinos are detected by the Super-Kamiokande (SK) far detector, which is a 50 kton water Cherenkov detector located 295 km away from the beam source in order to study neutrino oscillations. Since the far detector is capable of tagging neutrons, the observed beam-neutrino events can also be used to study neutron production associated with neutrino interactions in water.

T2K has completed the Run 1-9 data taking periods since the beginning of the data taking. In this thesis, all the Run 1-9 data corrected at the far detector, i.e. 14.938×10^{20} Protons On Target (POT) for the forward horn current (FHC) mode/ 16.346×10^{20} POT for the reverse horn current (RHC) mode are analyzed.

Development of neutron tagging algorithm

In the far detector, neutrons associated with neutrino interactions are quickly thermalized after they are produced, and are eventually captured by hydrogen nucleus with a typical timescale of 200 μs via the reaction:

$$n + \mathrm{H} \to d + \gamma \ (2.2\mathrm{MeV}). \qquad (0.0.1)$$

Since the capture produces a single 2.2 MeV γ ray, neutrons can be tagged by detecting the γ rays.

In this thesis, a neutron tagging algorithm is developed and is designed so that particular simulation dependence of neutron tagging efficiency is minimized as much as possible. The algorithm consists of two selection stages: the primary neutron candidate selection and the neural network classification. In the primary selection, neutron candidates are selected based on cluster of signals from photomultiplier tubes (PMT) in time. After the selection, there are numerous background events which are caused by accidental coincidences of random noise of PMTs. In order to remove efficiently these background events from the selected candidates, an artificial neural network with a set of 14 feature variables is used. The resultant neutron tagging efficiency and background event rate after the two selection stages are ~20% and 0.018, respectively.

Analysis sample

In this thesis, neutrons associated with neutrino interactions on water target are studied. It is therefore important to use ν event sample which is well known, studied, and established in terms of neutrino interaction cross sections and neutrino fluxes. For this purpose, the FHC and RHC 1R ν_μ samples used for the T2K oscillation analyses are used with a different definition of fiducial volume. The samples mainly consist of Charged Current (CC) Quasi-Elastic interaction and contain a high purity of ν_μ and $\bar{\nu}_\mu$ events for FHC mode and RHC mode, respectively.

Since neutrons produced near the inner wall of the far detector can escape from it before they are captured, a smaller fiducial volume compared to the one used in the T2K ν oscillation analyses is adopted.

The first application of neutron tagging to the T2K data

The neutron tagging algorithm is applied to the FHC and RHC 1Rν_μ samples. This is the first time to apply the neutron tagging technique to the T2K data. For each ν event in the 1Rν_μ samples, the algorithm is applied on an even-by-event basis.

Table 1 summarizes the number of observed neutrino events and number of tagged neutrons with the corresponding MC expectations. The observed neutrino events agree well with the expectations. On the one hand, for the tagged neutrons, the observation shows less tagged neutrons than that of expectations.

	Number of ν events		Number of tagged n	
	Expected	Observed	Expected	observed
FHC 1Rν_μ	202.12	201	64.08	44
RHC 1Rν_μ	109.61	110	49.42	33

Table 1: Summary of the number of neutrino events and tagged neutrons for the Runs 1-9 POT with the following oscillation parameter values: Δm^2_{21}=7.53 $\times 10^{-5}$ eV^2, Δm^2_{32}=2.452 $\times 10^{-3}$ eV^2, $\sin^2\theta_{23}$=0.532, $\sin^2\theta_{13}$=0.0212, δ_{CP}=-1.885, Mass Hierarchy = normal. All the expectations are normalized by the Run 1-9 POT.

Measurement of mean neutron multiplicity

Mean neutron multiplicity

Using the Run 1-9 FHC and RHC 1Rν_μ samples and the neutron tagging algorithm, mean neutron multiplicity is measured. Neutron multiplicity is expected to become large as the four momentum transfer squared Q^2 to the hadronic system at the primary ν-nucleus interaction increases. Since the direction of the beam neutrino is known, reconstructed muon transverse momentum P_t, which is a good indicator of Q^2, can be calculated. This analysis therefore measures the mean neutron multiplicity as a function of P_t given as:

$$\bar{M}_i = \frac{1}{\varepsilon_i} \times \frac{\left(N_{tag,i} - b \times N_{1\mu,i}\right)}{N_{1\mu,i}},$$

where i represents i-th P_t bin, $N_{tag,i} = \sum_{j=1}^{N_{1\mu,i}} m_{ij}$, $N_{1\mu,i}$ is number of observed 1Rν_μ events, m_{ij} is number of tagged neutrons of j-th 1Rν_μ event, b is accidental background event rate of the neutron tagging, and ε_i is neutron tagging efficiency.

It should be noted that this mean neutron multiplicity includes all the contributions from hadronic FSI and hadronic SI as well as primary neutrino-nucleus interaction.

Estimation of systematic uncertainties

Since the accidental background event rate is derived from T2K dummy spill data, only systematic uncertainties on the neutron tagging efficiency is considered. The considered systematic uncertainties are divided into 12 categories. Impacts of most systematic uncertainties are estimated to be very small. Systematic sources which affect neutron simulation, notably due to nucleon secondary interactions, and detector response for 2.2 MeV γ ray are estimated to be large. Total systematic uncertainty on neutron tagging efficiency is ∼8 %. Total systematic uncertainty on the averaged neutron tagging efficiency is estimated to be ∼8%.

Result

Figure 2 shows the measurement results in comparison to the expectations for three neutrino-nucleus MC event generators: GENIE, NEUT, and NuWro. As shown in the figure, the measured averaged mean multiplicity shows a tendency that the RHC sample has higher mean multiplicity than that of the FHC sample. Since in general CC $\bar{\nu}_\mu$ interactions produce more neutrons compared to CC ν_μ interactions, the observed tendency is consistent with the expectation.

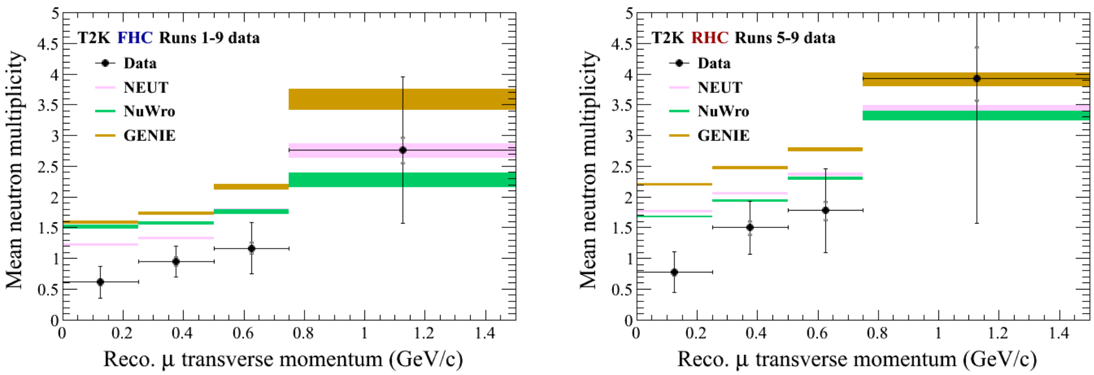

Figure 2: Mean neutron multiplicity as a function of reconstructed muon transverse momentum in comparison to the equivalent expectations of the NEUT-, NuWro-, and GENIE-based MCs. The left and right figures show the FHC and RHC 1Rν_μ samples, respectively.

The measured mean neutron multiplicity averaged over P_t is:

$$\text{Runs } 1-9 \text{ FHC } 1\text{R}\nu_\mu \text{ sample} : 1.00 \pm 0.17 \text{ (stat.)}^{+0.07}_{-0.08} \text{ (syst.) neutrons}/\nu \text{ event}$$
$$\text{Runs } 5-9 \text{ RHC } 1\text{R}\nu_\mu \text{ sample} : 1.40 \pm 0.26 \text{ (stat.)}^{+0.10}_{-0.11} \text{ (syst.) neutrons}/\nu \text{ event},$$

whereas the corresponding expectations of the NEUT-based MC are:

$$\text{FHC } 1\text{R}\nu_\mu \text{ sample} : 1.50 \pm 0.02 \text{ (stat.) neutrons}/\nu \text{ event}$$
$$\text{RHC } 1\text{R}\nu_\mu \text{ sample} : 2.14 \pm 0.02 \text{ (stat.) neutrons}/\nu \text{ event}.$$

The deviation from the expectation is 2.75 σ (2.69 σ) for the FHC (RHC) sample based on the total error of the measured value. This is the first measurement of neutrons associated with neutrino interaction in water for accelerator neutrinos and antineutrinos.